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ECONOMIC PROBLEMS OF INFORMATION AND ORGANIZATION

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1. Introduction

Research on the present contract during this report period falls under the following headings:

Econometric Studies of Education

General Theory of Resource Allocation

Empirical and Computational Research on Resource Allocation

Decision Rules for Reacting to Noisy Signals from a Warning System

General Theory of Decision and Organization

Brief summaries of results obtained and work in progress under each heading are presented in the following sections. The last sections list the Technical Reports and Working Papers, in which these results are reported in more detail, and the outlines of two volumes described in Section 5.

2. Econometric Studies of Education

It is by now commonplace to think of educated people in terms of "human capital," and it is well recognized that this capital is one of the most important factors of production. No special argument is needed, therefore, to motivate a study of education as a production process.

Considered as a production process, or set of processes, the formation of "human capital" has a number of special features. First, the process is a long one. Just considering formal education, the time spent in producing some output may vary from 10 years for a person leaving the school system at the minimum age, to 20 years or even more for a Ph.D. Second, education is highly "human intensive," and there are serious obstacles to pushing very far the substitution of non-human inputs for human inputs. This is not to minimize the importance of buildings, laboratories, libraries, television, teaching machines, etc., but for some years to come, at least, we can expect great resistance to impersonalization of teaching and learning. Third, the educational system is directly dependent on its own output for its human capital. Such dependence is found in other sectors as well, e.g., animal husbandry, but education is certainly unusual with regard to the complexity of this direct dependence.

These considerations suggest that a useful start on a detailed empirical description of formal education as a process of human capital formation might emphasize the dynamics of the process, and restrict its attention to human inputs and outputs. A mathematical model that seems adapted to such an effort is the von Neumann model of production, or linear activity analysis. As applied to education such a model would consist of a list of human inputs and outputs, classified by educational qualifications, together with an array of technical coefficients characterizing the transformation possibilities from one year to the next. Formally, the same classification is used for inputs and for outputs, so that the production process transforms a vector of quantities of stocks of students and teachers of various qualifications at the beginning of a year into another vector at the end of the year. In this process we distinguish between the new production of various outputs, and the carry-over of stocks from the preceding year (possibly with depreciation).

In "Educational planning for economic growth" (Technical Report 23), D. Koulourianos elaborates the activity analysis model of education, and compares a number of variants with respect to their potential usefulness for educational planning. He also reviews existing mathematical models of education, and the empirical evidence on the economic value of education. The activity analysis approach is illustrated with estimates of input coefficients for non-instructional human inputs at the University of California, Berkeley.

A first attempt at estimating a complete activity analysis model of an educational system is described in the paper by L. Nordell, "A dynamic input-output model of the California educational system." Actually, this model is a special case of the general activity analysis model, in that only one vector of coefficients is estimated for the activity of producing any single output. (A typical activity takes students of given qualifications at a given level--i.e., year in school--through one year of schooling in a given program.) The model covers the first grade (primary school) through the Ph.D., including teacher training, and is therefore "complete" in a dynamic sense. However, only part of the California system is represented. Coefficients for the primary and secondary levels are derived from statewide surveys of class sizes and teaching loads, and on curricula in the Los Angeles school district. Coefficients for higher education are based exclusively on data from the Berkeley campus of the University of California. No attempt was made in this paper to represent the State College or Junior College systems, or private schools.

Briefly speaking, this model of the technical relations within the educational system takes the following form. We specify a matrix A relating the gross outputs of the system in a given year to the inputs required in the previous year to produce that output. The technology matrix is assumed to remain unchanged over the planning period. By using a matrix relationship we are in effect postulating a homogeneity of degree one of the production relations; to raise all outputs by a given percentage one must raise all inputs in the same percentage.

We then make assumptions on the year-to-year survival pattern of teacher stocks and derive a relationship between a given year's inputs, that year's final demand, and the following year's inputs; the sum of the latter two vectors constitutes the total demand for a given year's output. All that remains to make the model operational then is a specification on the post-horizon behavior of the system. This is done, as we shall discuss below, by specifying a special type of balanced growth after the horizon of the planning period; then the model operates in a recursive fashion from the horizon back down to the present. Using the results of this initial operation, the educational planner may revise his initial hypotheses on the post-horizon behavior (or on any other variable aspects of the system with which he is working) and operate the model on a doubly iterative basis until his expectations of the system's time path tend to converge sufficiently.

The Nordell model takes as exogenous the "final demand" for the output of the educational system (i.e., the demand for educated persons who are not themselves used in the educational system).

The initial set of projections of final demand for education was derived from a fairly simple demographic model. The basic assumption was that final demand for education from all sources, say labor force demand plus consumption demand, is measured by the net output from one year to the next, of the educational system. This was taken for a base year of 1965-66. In order to make a set of predictions for the annual growth of final demand, it was necessary to assume some relationship between final demand and employment. The assumption made was that the growth of final demand is at the same rate as the growth of the annual increments to the labor force. Since the output of the educational system supplies the bulk of this increment, the major assumption used was that the total annual final demand grows in proportion to its labor force demand component. Three different projections for the growth of the civilian labor force were used, two for the U. S. as a whole, and one for California.

Using his complete model, Nordell was able to project required enrollments and teacher stocks through 1980 on the assumption of balanced growth after 1980. In spite of certain weaknesses in the estimates of the coefficients and the projections of final demand (discussed below), it is of interest to compare the model requirements with actual enrollments for 1966. Roughly speaking, the model requires about ten percent higher enrollments in the primary and secondary schools than are actually enrolled, whereas requirements are more than fifty percent higher than enrollments at the college level. This suggests that California is not currently training enough college graduates to take care of the final demand for educated persons in the next couple of decades, if one takes account of the requirements for training teachers as well as those who go into the non-teaching sector of the economy.

The Nordell model should be extended and improved in two directions, and work is being carried forward currently on this. First, input coefficients are being estimated for state colleges and for junior colleges in California, and nationwide averages will be estimated for several types of institution of higher education from Office of Education data. This will permit projections of requirements on a nationwide basis. It will also permit a significant increase in the level of sophistication of the model, in that it will permit the description of alternative technologies for the process of higher education (technologies depending on the type of school and on the quality of inputs and outputs). The formulation of alternative technologies will lead to a full activity analysis--or linear programming--approach, rather than the more restrictive input-output approach, and will thus permit some degree of optimization of the system, rather than just unique projections of requirements derived from projections of final demand.

Second, improvements are needed in the method of projecting final demand for educated persons. Nordell used projections of the total labor force, and some crude assumptions about the distribution of education in the labor force. The problem of how to predict final demand for education is an extremely difficult one; a survey of methods and experiments that have thus far been tried has been prepared by D. Adkins. Even historical statistics on the composition of the teaching and non-teaching labor force by level and type of education are not directly available in sufficient detail, and D. Adkins is preparing such estimates from various sources, for the recent past. (These estimates should be available sometime during the summer of 1968.)

3. General Theory of Resource Allocation

Considerable research under the present contract has been devoted to extending the theory of resource allocation to more adequately deal with time and uncertainty.

It is a well-known proposition of economic analysis that, under "classical" assumptions of non-increasing returns to scale, non-increasing marginal productivity, continuity, etc., an efficient production program also maximizes the value of net output if value is calculated using suitable prices. In a dynamic context, in which commodities are distinguished according to the date at which they are used or made available, the value of the production plan is "present value," and the price system includes discounted future, as well as present, prices.

The extension of this theory to the case of an infinite planning horizon poses certain mathematical difficulties, which in turn raise conceptual problems concerning the proper definition of "price" and "present value." Radner's paper, "Efficiency prices of infinite horizon production programs" (Technical Report 26), extends the usual theory of efficiency prices to the case of an infinite planning horizon (discrete time), and analyzes the relationship between two alternative approaches to the definition of price systems in this case: the linear functional approach and the price sequence approach. For the linear functional approach, the paper characterizes efficient programs in terms of maximizing present value, and shows that all efficient programs can be approximated by efficient programs whose corresponding price systems are strictly positive. A linear functional price system can be decomposed into a series part and an asymptotic part. The price sequence approach (Malinvaud) gives prices that can be derived as limits of price ratios from the series part of linear functional price systems, as one approximates the given efficient program by programs with strictly positive prices. Bounds are given for the growth of output; under "classical" assumptions, for any fixed sequence of exogenous supplies of primary resources one can choose measurement units at each date so that all feasible programs converge uniformly to zero at any desired rate.

The theoretical development in the above-mentioned paper required an extension to infinite-dimensional spaces of the Arrow-Blackwell-Barankin theorem characterizing maximal points of convex sets. This is done in Radner's paper, "A note on maximal points of convex sets in ℓ_∞" (Technical Report 22).

Let X be the Banach space of all bounded sequences of real numbers, with the sup norm topology, and partially ordered coordinatewise (i.e.,

$x = (x_n)$ is $\geq x' = (x'_n)$ means that $x_n \geq x'_n$ for every n). Let Y be the space of all continuous linear functionals on X, with the weak* topology, and define $y \geq 0$ to mean $y(x) \geq 0$ for all $x \geq 0$ in X, and $y \gg 0$ to mean $y(x) > 0$ for all $x \geq 0, x \neq 0$ in X. Let S be the set of all non-negative y in Y with norm 1, and let S^+ be the set of all $y \gg 0$ in S. It is shown that if $\hat{x}$ is maximal in a compact convex subset C of X, then there is a $\hat{y}$ in S such that (1) $\hat{x}$ maximizes $\hat{y}(x)$ on C, and (2) $(\hat{x},\hat{y})$ is the limit of a generalized sequence (x^m, y^m) of points in CxS^+ such that for each m, x^m is maximal in C and maximizes $y^m(x)$ on C.

The general theory of allocation of resources under uncertainty was pioneered by Arrow (1953) and Debreu (1959)* Arrow's formulation, however, did not take account of time, and implicitly assumed that all economic agents had the same information. Debreu extended the Arrow analysis to a market for dated commodities, but retained the assumption that all agents had the same information.

For a long time economists have praised the market economy for its efficiency in the use of information and for its economy in the use of communication. In fact, it was supposed that the mere communication of prices could replace, without loss, the communication of available techniques and complex descriptions of the preferences of consumers. But a serious study of information requires a theory that takes account of uncertainty, and a study of the exchange of information only makes sense if one supposes that the various economic agents have different information, at least before the exchange occurs.

In the paper, "Competitive equilibrium under uncertainty" (Technical Report 20), Radner explores how far one can go in applying the modern theory of competitive equilibrium to the case of uncertainty. In the first part, the analyses of Arrow and Debreu are extended to the case in which different economic agents may have different information about the environment. The second part deals with the limitations of the Arrow-Debreu type of model, and discusses the difficulties associated with non-convexities in the production of information, with information generated by spot markets, and with limitations on the computational capacities of economic agents. It is argued that the demand for liquidity arises from, among other things, the last two phenomena, and thus does not appear to be amenable to analysis by means of the "neoclassical" theory of competitive equilibrium.

As indicated above, one can extend Debreu's theory to the case in which the agents do not necessarily have the same information. But the resulting theory requires that the agents possess capabilities of imagination and calculation that exceed reality by several orders of magnitude. Further, this theory requires a system of insurance and futures markets that is too complex, too detailed and too refined to have any practical significance.

In the present "market economies," there is a sequence of markets, each one of which is composed of spot, futures and insurance markets, the spot markets being the most important. In such markets, at each period prices serve as

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*K. J. Arrow (1953), "Le rôle des valeurs boursières pour la répartition la meilleure des risques," Econométrie, Paris, Centre National de la Recherche Scientifique, pp. 41-48; or see the translation, "The role of securities in the optimal allocation of risk bearing," Review of Economic Studies, Vol. 31 (1964), pp. 91-96.

G. Debreu (1959), Theory of Value (New York: Wiley).

signals in the information structure of the agents. But the agents are interested in predicting the dependence of future prices on environmental events. To make such predictions they must in principle know the plans of the other agents, because prices at a given date also depend on previous decisions as well as on surrounding events.

The agents therefore have an interest in the realization of an equilibrium that insures the consistency not only of the individual plans but also of the price predictions.

In Radner's paper, "Equilibrium of spot and futures markets under uncertainty" (Technical Report 24), an equilibrium is defined, roughly speaking, as a consistent set of plans, current spot and "futures" prices, and conditional forecasts of prices on markets in the future. For the economy to achieve an optimum, relative to a given structure of information, economic agents must be able to buy insurance against changes in spot prices. It is shown that an equilibrium (in the above sense) may be an optimum if the producers can insure against all risks in their production by using the equilibrium predictions. But if this last condition is not met, the theory suggests that markets are not able to provide an optimal solution to the problem of choosing investments in the face of an uncertain future. Such a situation could justify public intervention.

An important aspect of this theory is the role that future prices play in the information structures of economic agents. The paper concludes that indicative plans should give estimates of prices that are not unique but that are conditional on future events. This theory also suggests that a larger role should be attributed to insurance against future price changes (e.g., to salaries, annuities, etc. that are tied to price indices).

In a decision problem under uncertainty, one is often interested in how an increase in uncertainty affects the optimal decisions, or, more sharply, in comparing the optimal decisions under uncertainty with the optimal decisions for some "corresponding" decision problem under certainty. In such a context, the "certainty equivalence theorem" states that, if the payoff function is quadratic in the outcome variables, its quadratic term being negative definite, if the relations between decision variables and outcome variables are linear and are stochastic only by additive random disturbances, if these disturbances have zero expectations and are independent of the decision variables, then the optimal decisions are the same as if there were no uncertainty, i.e., as if the disturbances were identically zero.

As was first shown by H. Simon (1956) and H. Theil (1957), this property generalizes to a dynamic problem; more precisely, if the decision maker does not forget any information through time, then for the optimal decision functions, the <u>initial</u> decisions, and the <u>expected values</u> of the <u>subsequent</u> decisions, are the same as if the disturbances were identically zero.

In his paper, "First-order certainty equivalence" (Technical Report 27), Malinvaud shows that the dynamic certainty-equivalence theorem holds to a first order of approximation if the uncertainty is "small," i.e., as the variances of the disturbances tend to zero. Malinvaud also applies the theorem to a specific problem of allocation of resources under uncertainty, and shows why it is so difficult to characterize the situations in which an increase in the degree of uncertainty requires a decrease in the allocation of resources to the risky projects.

4. Empirical and Computational Research on Resource Allocation

The theoretical research described in the previous section points to and emphasizes the importance of information in the operation of the market mechanisms hypothesized by the "classical" theory of resource allocation. To our knowledge, the first systematic attempt to measure the information requirements of a real market was made by P. Schmidbauer in his paper, "Information and communications requirements of the wheat market: an example of a competitive system" (Technical Report 21). Using the American wheat market as a prototype, Schmidbauer developed a computer model of the information processing activities of a competitive system. The particular model used the framework of the theory of teams (Marschak and Radner), and certain hypotheses about individual decision-making suggested by the work of Simon, Cyert, and March. On the basis of the model, and using data from various sources, the information processing resources required for short-run decisions were estimated in terms of computer hours, memory capacity, and volume of communication. The results may be crudely summarized by saying that the American wheat market requires an amount of information processing roughly equivalent to that which could be done by thirty IBM-7090's operating full-time, around the clock, throughout the year (this is an average for the year, and does not take account of peak loads). There would also be about 29,000 reels of tape (2500') to meet the information storage requirements.

In addition to the theoretical research on resource allocation described in the previous section, a new algorithm was developed for optimal resource allocation over time, which combines the recursive features of dynamic programming with the exact formulas for optimal solutions in the so-called "linear-logarithmic case" (Radner, 1964, 1966; Radner and Friedmann, 1964; Friedmann and Wilson, 1965). Actual computational experience with the algorithm to date indicates that it is efficient for handling a fairly large number of variables over a time horizon of more than 50 periods. It takes advantage of the recursive nature of decisions in time, which general algorithms of non-linear programming typically do not, and yet the memory and computing requirements go up only linearly with the number of state variables, instead of as the power of the number of state variables, as in the case of the general dynamic programming technique.

Various results on this algorithm are reported in S. Friedman's paper, "An algorithm for dynamic programming of economic growth" (Technical Report 28). Through numerical experimentation, Friedman studies in some detail the computational properties of the algorithm. He also applies the algorithm to an empirical model of the U. S. economy, and compares various optimal paths with the observed path of the economy from 1910 to the present.

The computer has also been used as a tool of analysis in a current study of alternative procedures for decentralized allocation of resources. This work is an outgrowth of the paper "Decentralized procedures for planning," by E. Malinvaud.* Following certain ideas in his previous paper, in the Spring and Summer of 1967 Malinvaud elaborated several new decentralized procedures

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*Technical Report 15, later published as Chapter 7 in Malinvaud and Bacharach, eds., Activity Analysis in the Theory of Growth and Planning (New York: St. Martin's Press, 1967).

that promised to be more consistent with the availabilities of information in actual economic planning than the standard decomposition methods of linear and non-linear programming. The four procedures are being studied by T. Hogan, in the context of a simplified linear activity analysis model of an economy. Two of the four procedures have been tested on 2- and 5-sector models and found to operate in a satisfactory manner. A third procedure was tested and failed, but it may be possible to modify it so that it will work. The fourth procedure has not yet been tested, because of computer programming difficulties. The next stage is to use numerical experiments (i.e., simulation) to compare the procedures with respect to their efficiency. These comparisons will be made for both deterministic and stochastic environments. (For a formulation of the problem and a summary of results obtained to date, see T. Hogan, "A preliminary investigation of four planning models," Working Paper No. 243.)

5. Decision Rules for Reacting to Noisy Signals from a Warning System

Consider a decision maker, or network of decision makers, connected to a warning system (or themselves part of a warning system). The warning system is supposed to signal the occurrence of an event (or events) that requires some definite action; however, the signals are noisy, so that from time to time warning signals may appear when no action is actually required. When warning signals are received, the decision maker may act immediately, or he may wait for more information. If action is really required, then delay is costly; whereas if no action is really required, then action is costly. For example, the signals may warn of an attack, or may warn of the breakdown of equipment.

A natural class of decision rules that suggests itself in this situation is to have the decision maker test at each moment of time the hypothesis that action is already required (e.g., that an attack has already occurred, or that the equipment has already broken down), for example by using a maximum likelihood ratio test. One does not expect a rule of this sort to be truly optimal, since it does not, in principle, take account of the advantages to be gained by waiting for more information. On the other hand, such a rule might turn out to be quite good.

In previous unpublished work, Radner showed that if (1) there are several warning signals intended to warn of the same event, with the noise in the several signals being statistically independent, (2) each signal is of the zero-one (on-off) type, and the effect of noise in a signal is to give a "false alarm," (3) a false alarm is automatically turned off (i.e., the failed signal device is restored to correct operation) after some period, (4) the elapsed times to failure and the elapsed times to restoration are independent random variables with geometric distributions (not necessarily the same), then the maximum likelihood ratio rules have the following form: for each subset S of signals there is "critical value," say w_S, such that the decision maker should act as soon as, for any set S, all of the signals in the set S have been in a state of failure for at least w_S units of time.

If we call decision rules of this last type "critical value" decision rules, then the above result can be stated as: under the stated conditions, the maximum likelihood ratio (MLR) rules are critical value rules.

As a criterion for judging alternative rules, Radner proposed the following: a decision rule is called efficient if no other rule has a longer expected time to action given that no action is required, without at the same time having a longer expected time to action given that action is required.

Using the method of Markov chains, Radner and Tjian showed by numerical examples that, within the class of critical value rules, the MLR rules could be efficient in certain cases in which the failure rate of the signal mechanism was relatively large, but inefficient in other cases in which the failure rate was relatively low. (See T. Y. Hans Tjian, "A note on maximum likelihood ratio decision rules for simple noisy warning systems," Working Paper No. 249.)

By making certain assumptions about the costs of wrong decisions, it has been possible to formulate the problem as a dynamic programming problem of the usual form. It is conjectured that in this form the optimal decision rules can be shown to be of the critical value type; it is also hoped that conditions can be found under which the optimal rules will be MLR rules.

6. General Theory of Decision and Organization

The manuscript of a book, Economic Theory of Teams, has been completed by Radner and J. Marschak (UCLA). This volume incorporates the results on the theory of teams that have been obtained by the authors over the past ten years.* The manuscript has been read by R. Selten, and, after some minor revisions, will go to press in the summer of 1968. (Publication will be by Wiley, Inc., in the Cowles Foundation Monograph Series.)

A volume, Decision and Organization, has been put together by Radner and C. B. McGuire (as editors), with contributions from K. J. Arrow, M. Beckmann, G. Debreu, L. Hurwicz, T. C. Koopmans, T. A. Marschak, C. B. McGuire, R. Radner, H. Scarf, and H. Simon.* This volume is intended as an exposition and review of major developments in the economic theory of decision and organization of the past fifteen years or so, and will be dedicated to Jacob Marschak. A major part of the research covered has been supported at least in part by the Office of Naval Research. The aim of the volume is to make these results more accessible to graduate students in economics, operations research, and management science, and in so doing to honor Jacob Marschak, who has played such an important role in the development of this field. The manuscript will probably be ready to go to press during the summer of 1968.

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*See outline attached in Sections 8 and 9.

7. List of Technical Reports and Working Papers Referred to, With Publication Information Where Appropriate

Technical Reports

No. 20 R. Radner, "Competitive equilibrium under uncertainty," April 1967 (revised). To appear in Econometrica, Vol. 36 (1968).

No. 21 P. Schmidbauer, "Information and communication requirements of the wheat market: an example of a competitive system," January 1966.

No. 22 R. Radner, "A note on maximal points of convex sets in ℓ_∞," January 1966. Published in Proceedings of the Fifth Berkeley Symposium on Probability and Statistics, Vol. 1 (Berkeley: University of California Press, 1967).

No. 23 D. Koulourianos, "Educational planning for economic growth," February 1967.

No. 24 R. Radner, "Equilibrium of spot and futures markets under uncertainty," April 1967. Published in Cahiers d'Econometrie, No. 9 (1967), pp. 30-47.

No. 25 L. Nordell, "A dynamic input-output model of the California educational system," August 1967.

No. 26 R. Radner, "Efficiency prices for infinite horizon production programs," January 1968. Published in Review of Economic Studies, Vol. 34 (1967), pp. 51-66.

Technical Reports in Preparation

No. 27 E. Malinvaud, "First-order certainty equivalence," to appear in April 1968.

No. 28 S. Friedmann, "An algorithm for dynamic programming of economic growth," to appear in April 1968.

Working Papers

No. 243 T. Hogan, "A preliminary investigation of four planning models," January 1968.

Working Papers in Preparation

No. 249 T. Y. Hans Tjian, "Maximum-likelihood-ratio decision rules for simple noisy warning systems," April 1968.

D. Adkins, "Educational planning for trained manpower" (in preparation).

8. Outline of DECISION AND ORGANIZATION, A Volume in Honor of Jacob Marschak, Edited by R. Radner and C. B. McGuire

1. Introduction (Radner)

Preferences

2. Choice and Uncertainty (Arrow)
3. Representation of Preference Orderings with Independent Components of Consumption (Koopmans)
4. Representation of Preference Orderings Over Time (Koopmans)

Information

5. Measurement and Comparisons of Information (McGuire)
6. The Technology of Information (McGuire)
7. The Demand for Information (Arrow)

Individual Decision

8. Theories of Bounded Rationality (Simon)
9. Decision over Time (Beckmann)

Group Decision - Organization

10. Normative Theories of Organization (Radner)
11. Computations in Organizations (T. Marschak)
12. Teams (Radner)
13. Allocation of a Scarce Resource under Uncertainty: An Example of a Team (Radner)
14. The Limit of the Core of an Economy (Debreu and Scarf)
15. Informational Decentralization of an Economy (Hurwicz)

9. Outline of the Volume, ECONOMIC THEORY OF TEAMS, by J. Marschak and R. Radner

CHAPTER VII. THE TEAM IN A DYNAMIC ENVIRONMENT